HURRICANE EDNA, 1954

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INTRODUCTION

Hurricane Edna was the second tropical storm of 1954 to penetrate the east coast of the United States, the center reaching into New England on September 11, some 11 days after Hurricane Carol. While total loss of life and damage to property for Edna were less than for Carol, the tracks were similar. A reexamination of some of the meteorological conditions associated with the formation and movement of Edna may reasonably be expected to have elements in common with other storms of similar life history. Coincidentally, while this article was being written, Hurricane Hazel, about one month after Edna, moved inland across the South Carolina coast on October 15, and accelerated northward, maintaining exceptional intensity for a tropical storm moving over land. Although Edna was the least spectacular of the three hurricanes, its occurrence in September calls for it to receive most of the authors' attention as a contribution to the review of September's weather. Only incidental references are made to Carol and Hazel.

THE FORMATION OF EDNA

The first surface indication of an apparently closed circulation that subsequently evolved into Hurricane Edna was noted the night of September 5, in the extreme southwestern Atlantic between Puerto Rico and the Bahama Islands. Some forewarning of the possible formation of a tropical storm was given by a 2100 GMT, September 5 ship report from a position near 22.5° N., 67.7° W. This report from *The Bulk Oil* stated that she was encountering very heavy squalls, winds to 50 m. p. h., with gusts to 70 m. p. h., and rapidly falling barometer.

As is usual when storms form along the West Indies, Edna developed within an extensive easterly wave that had recently moved into the region. Another indication of possible cyclogenesis was the intense rainfall experienced over Puerto Rico with the passage of the easterly wave. Widespread rain had been observed at the regularly reporting stations; however, it was not until the receipt of a bulletin from San Juan on September 7, after the formation of Edna was an established fact, that the extent of this rainfall was realized. The bulletin from San Juan stated that intense rains had flooded the entire southern and western coastal sections of the Island, some stations reporting more than 4 inches of rain in a 24-hour period, while other sections had more than 10 inches during a 2-day period. With respect to convective rain, at any rate, the easterly wave within which Edna formed, showed exceptional activity in the day or so prior to formation of the storm.

Several ship reports on the surface chart for 0030 GMT, September 6, gave more positive indications that a tropical storm was developing in the region just northeast of Santo Domingo. At this time the center was located at 21.6° N., 68.5° W. While the winds had not yet reached hurricane force, the first advisories at that time predicted intensification.

THE TRACK OF EDNA

Prior to 1830 GMT, September 6, ship reports in the immediate vicinity of the storm were sparse, and therefore the positions shown for the storm track (fig. 1), in this time interval, should be viewed with some skepticism. Likewise, the loops shown in the track, while based on a careful consideration of the few reports available at the time, are not certain features, except with respect to very slow movement of the center at the respective positions. The final track, as pictured in figure 1, takes into consideration all available ship and island reports, aircraft reconnaissance, land-based radar reports, and Weather Bureau bulletins.

In the period prior to recurvature, 0030 GMT, September 6 to about 1830 GMT, September 9 inclusive, the track appears to have a rather uniform oscillation of small amplitude with period of about 26 hours. The regularity of these oscillations prior to recurvature compares quite favorably with those pictured by Yeh [1], who has developed the following interesting yet simple formula relating the period of oscillation with several variables pertaining to the low level structure of a hurricane:

$$T=\frac{4\pi R^2}{2v_0r_0-fR^2}$$

where T is the period, v_0 is the maximum wind speed, r_0 is the distance from the center to v_0, f is the Coriolis parameter and R is the radius over which air is assumed to move

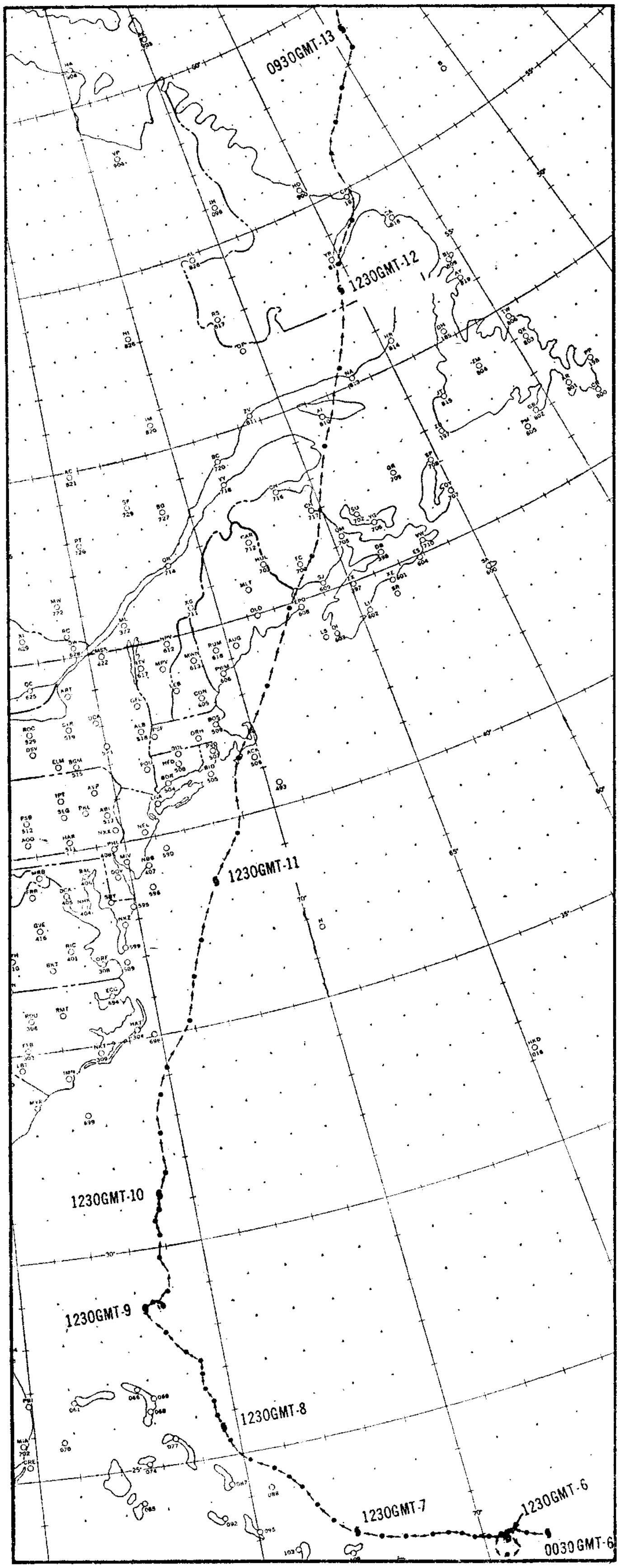
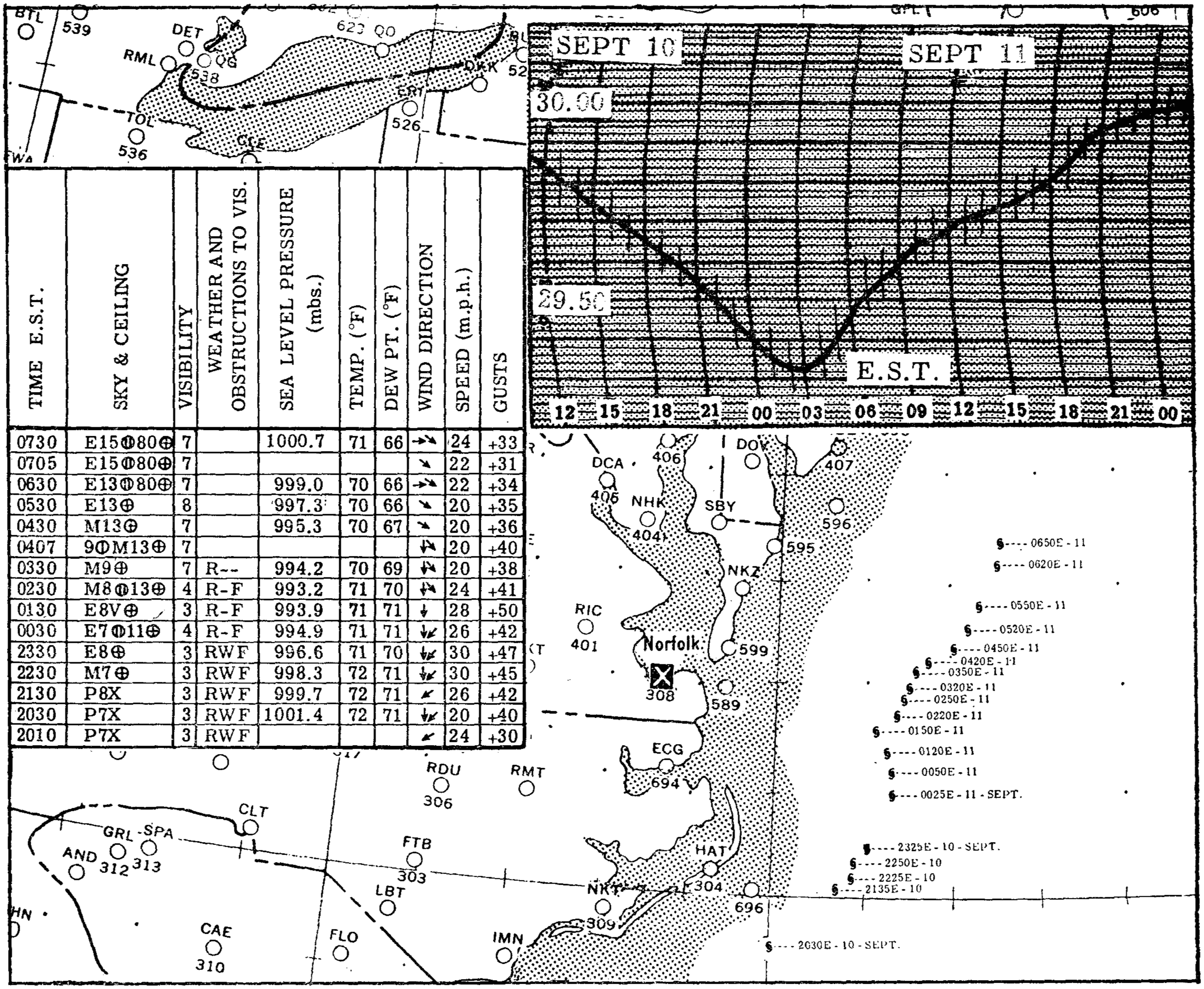


FIGURE 1.—The track of Edna, shown in 3-hourly intervals.

with the vortex. As the 26-hour period of oscillation in the 3-day interval was judged to be accurate to within 10, and possibly 5 percent, T, the period, was used as one of the "knowns" in making a trial substitution into Yeh's equation. For the maximum wind, the value of 120 m. p. h., from the *Fairland* in the forward semicircle, agreed quite well with the report of maximum wind slightly over 100 knots received from reconnaissance. Also, along this portion of the track, a reasonably accurate estimate for the diameter of the eye, obtained by averaging the values from a number of reconnaissance reports, was 25 miles. With the eye itself having a radius of just over 10 miles, a compromise between several reports on the extent of the region with maximum winds indicated that a total distance of 25 miles out from the center was a reasonable estimate for the radius distance to the maximum winds. Substitution into Yeh's formula, using 0.6×10^{-4} sec.$^{-1}$ for the Coriolis parameter, gives about 95 miles for the value of R, which result may be looked upon as the radius of the storm. This value was considered to be of the right order of magnitude. However, in working further with the equation, it soon became apparent, as recognized by Yeh [1], that even for a small storm, much more detailed observational data than now currently available would be required to test or apply the relationships involved. In attempting to solve for the period, several trial computations have indicated that only small changes in the other variables, within present limits of observation, lead to large differences in the resulting period. The equation is very sensitive to v_0, r_0, and R, such that there is little hope, at present, of applying the formula with expectations of specific and consistent results.

Soon after 1230 GMT, September 9 and until about 2130 GMT of the same day, aircraft reconnaissance radar reports became confusing. For example, the center was at times reported to be stationary, followed by a report indicating a sudden displacement southeastward; still a later report again mentioned stationary, and subsequently another indicated a sudden northeastward movement. A careful post-analysis indicates that some of the reports were inconsistent. It has been shown that errors in interpretation of radar echoes have occurred [2], and some may be due to the fact that the beam picks up the nearest squall band which may blot out possible echoes from behind the band. Occasionally, false eyes have been encountered [3], as proven by instances when the mistakes were subsequently discovered by the reconnaissance aircraft while in flight, and corrected messages sent. This happened at least twice during the reconnaissance of Edna.

Some of the difficulties and disappointments in accurately locating the eye of a storm may be caused by the eye often being in a state of flux, and, in particular, frequently possessing an isolated and centrally located cloud [4] of variable size, such that, to an aircraft in flight, the central cloud bank may visually blend in with the true outer cloud walls of the eye. It is therefore apparent that a storm track such as ours of Edna, does not begin to re-



TIME E.S.T.	SKY & CEILING	VISIBILITY	WEATHER AND OBSTRUCTIONS TO VIS.	SEA LEVEL PRESSURE (mbs.)	TEMP. (°F)	DEW PT. (°F)	WIND DIRECTION	SPEED (m.p.h.)	GUSTS
0730	E15⦶80⊕	7		1000.7	71	66	→↘	24	+33
0705	E15⦶80⊕	7					↘	22	+31
0630	E13⦶80⊕	7		999.0	70	66	→↘	22	+34
0530	E13⊕	8		997.3	70	66	↘	20	+35
0430	M13⊕	7		995.3	70	67	↘	20	+36
0407	9⦶M13⊕	7					↓↘	20	+40
0330	M9⊕	7	R--	994.2	70	69	↓↘	20	+38
0230	M8⦶13⊕	4	R-F	993.2	71	70	↓↘	24	+41
0130	E8V⊕	3	R-F	993.9	71	71	↓	28	+50
0030	E7⦶11⊕	4	R-F	994.9	71	71	↓↙	26	+42
2330	E8⊕	3	RWF	996.6	71	70	↓↙	30	+47
2230	M7⊕	3	RWF	998.3	72	71	↓↙	30	+45
2130	P8X	3	RWF	999.7	72	71	↙	26	+42
2030	P7X	3	RWF	1001.4	72	71	↓↙	20	+40
2010	P7X	3	RWF				↙	24	+30

FIGURE 2.—Composite chart showing barograph trace from Norfolk, Va., radar reports from the same vicinity, and simultaneous surface observations from Norfolk.

veal the smaller scale, but nonetheless significant, variations in eye structure and relative position.

While the report by Gutenberg [5] concerning the usefulness of microseisms in tracking hurricanes is encouraging, the authors have not given attention to this aspect of Edna, based on information from Kammer [6] and Dinger [7], that the microseismic technique for the tracking of tropical storms is no longer looked upon with as much enthusiasm as several years ago. Among the reasons given for this change of opinion is doubt that the signal is generated in the immediate vicinity of the hurricane; it is thought rather that the energy is introduced into the earth by some type of wave action at variable and considerable distances from the storm.

LAND-BASED RADAR REPORTS ALONG EDNA'S TRACK

Radar reports from the vicinity of Norfolk, Va., and records of synoptic reports from Norfolk itself, describe vividly the sequence of weather as Edna approached these stations from the south-southwest and passed about 120 miles to the east on a track to the north-northeast. Figure 2 is a composite, which includes the detailed track of Edna as determined by radar from this vicinity. The barograph trace and surface observations in the figure are from Norfolk.

The radar reports show that at 0150 EST, September 11, the eye of Edna was closest to Norfolk. The barograph trace shows that although pressure began to level off at

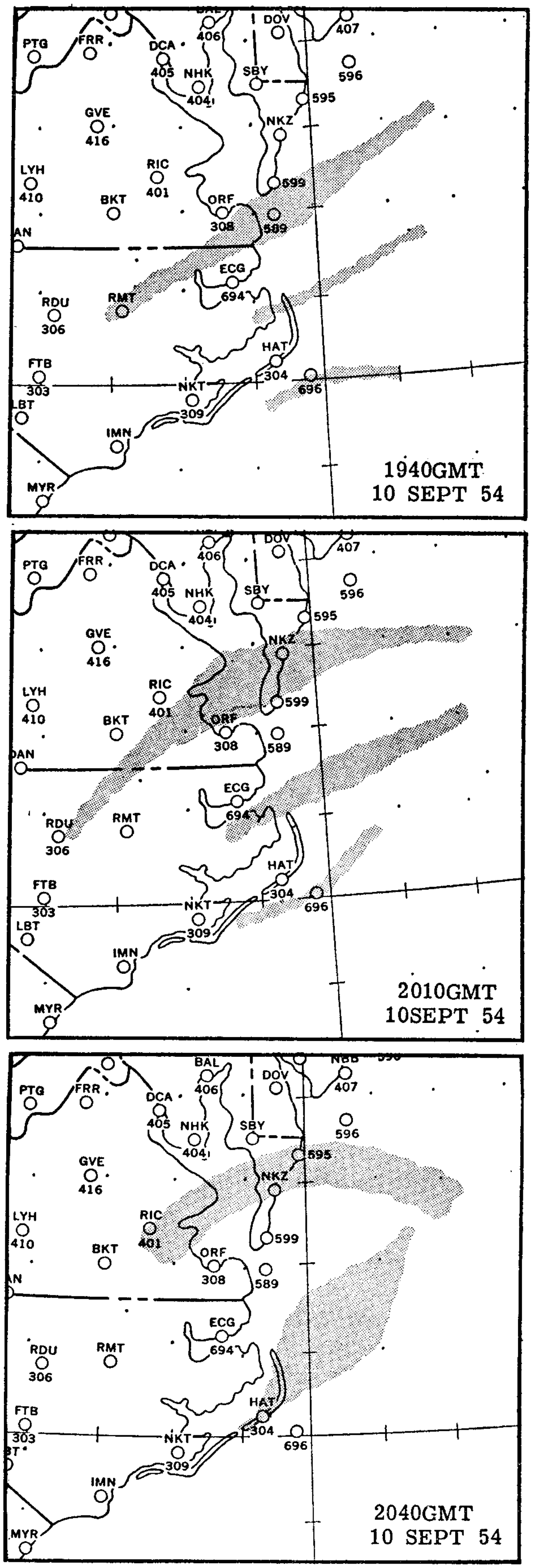


FIGURE 3.—Plot of radar echoes as observed from the Norfolk, Va. area, showing the rapidity with which spiral bands change shape and size.

about that time, it actually continued to fall until about 0230 EST. A degree of eccentricity in the associated structure of the storm is therefore indicated. The strongest sustained winds at Norfolk were 30 m. p. h., with gusts to 50 m. p. h. It was noted that with the passage of Edna to the northeast and the shift of surface wind from northeasterly to northwesterly, the temperature remained practically constant, while the dew point dropped perceptibly.

Before the eye of Edna approached to within radar range of the Norfolk vicinity, spiral rainbands were observed and recorded every half hour from 1910 GMT, September 10 to 0110 GMT, September 11. Three successive plots of these rainbands are reproduced in figure 3 showing how the rainbands changed in shape and orientation with time. It was interesting to find that the perpendicular bisectors of the chords across each of the band end points in every instance crossed the track in advance of the eye. This crossing of the track of the storm, by the perpendicular bisector, ahead of the eye, is geometrically consistent with bands located in the northwest quadrant that are spiralling in toward the center.

DEVELOPMENTAL STAGES

The storm was in the formative stage (Riehl [2]) by 1830 GMT September 6, (fig. 4), judging from a fairly dense coverage of ship and island reports. At that time, the strongest winds, while still below full hurricane force, were concentrated north and east of the deepening center. Lowest surface pressure was about 1,000 mb. In the following 18 hours, Edna continued to move slowly toward the west-northwest.

At 1830 GMT, September 7 the storm veered slightly toward the northwest (fig. 1). Edna then appeared to be in the immature stage (fig. 5), characterized by rapidly falling central pressure, full hurricane-force winds, as reported by reconnaissance, in an apparently tight ring

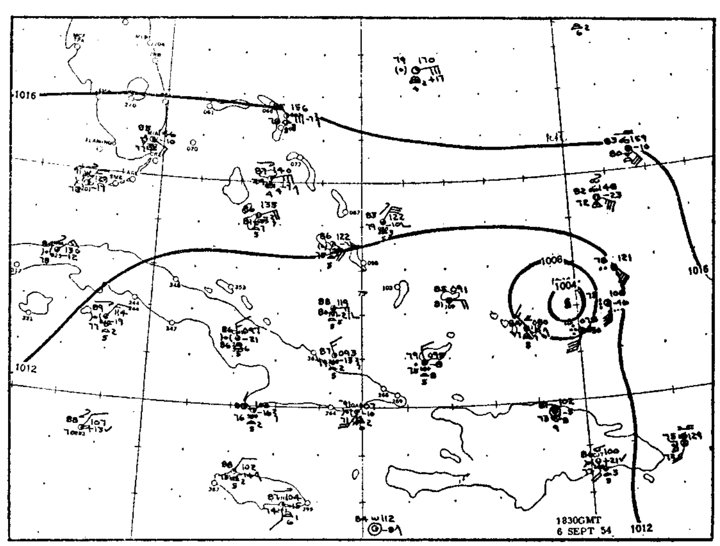


FIGURE 4.—Surface weather chart for 1830 GMT, September 6, 1954. The usual plotting model was used, except visibilities were omitted. At this time Edna was considered to be in the formative stage.

around the center, with squalls and spiral cloud bands in the process of becoming organized. Reconnaissance reports of minimum pressure gave 1,001 mb. at 1430 GMT, September 7, and 992 mb., 5½ hours later. As yet, the storm covered only a relatively small area. By mid-day September 7, aircraft reconnaissance was regularly sending radar fixes of the eye, along with other pertinent information. As all ships in the area were then attempting to give wide berth to Edna,[1] these radar fixes were invaluable for tracking the storm and estimating its development. Some of the remarks received from reconnaissance aircraft, descriptive of conditions near the eye on September 8, while the storm was in this immature but developing stage, are as follows:

0330 GMT. Altitude 8,000 feet. Eye position is center of 20 mile diameter hole [in radar echo] to sea. Weather band pattern on radar very confused. Positions in previous two reports based on horseshoe shape at end of weather band and believed in error by 25 miles too far north.

0430 GMT. Altitude 8,000 feet. Eye is circular hole [in radar echo] to sea, 20 miles diameter, fix believed accurate. Weather bands intensified slightly past hour but do not clearly define eye. Heaviest weather northern semicircle.

0530 GMT. Eye now fairly well defined by weather and sea. Squall bands extend 80 to 100 miles northern semicircle and 70 miles southern semicircle from eye.

0630 GMT. Altitude 8,000 feet. Definite increase in size and number of weather bands, now well developed spiral, equally [developed] in northeast quadrant during past hour. Eye well defined, circular, 20 miles diameter.

0730 GMT. Altitude 8,000 feet. Weather increased slightly in extent and intensity all quadrants, especially northwest quadrant near eye during past hour. Prominent spiral band now extends 140 miles north of eye. Eye will defined on radar.

0900 GMT. Altitude 8,000 feet. Now able to pick up eye at 90 miles [from eye]. Previously had to run in to within 30 to 40 miles [of eye]. Squalls now extend 100 miles from eye south semicircle and 150 miles north semicircle. Radar sea return [echo] indicates surface winds of about 80 to 90 knots near eye in northern semicircle. Squalls still intensifying all quadrants. Departing storm area.

1000 GMT. Radar indicates Edna developing rapidly. Lost eye at 150 miles [from eye].

[1] One ship, the *Fairland*, was caught in the eye and was seen from the reconnaissance aircraft flying in the eye [4].

A portion from one of the surface maps during the interval when Edna was in the mature stage, is shown in figure 6. From all indications, the central pressure had stopped falling, while simultaneously, the circulation had been expanding and the radius of hurricane-force winds had increased. Scarcity of data precludes positive verification that the storm lost symmetry and that the area of bad weather had extended itself farther to the right of the motion than to the left, both of the above features being typical of the mature stage.

Edna had little effect on continental United States until several hours after 1830 GMT, September 9. It was then that the storm accelerated almost directly northward in

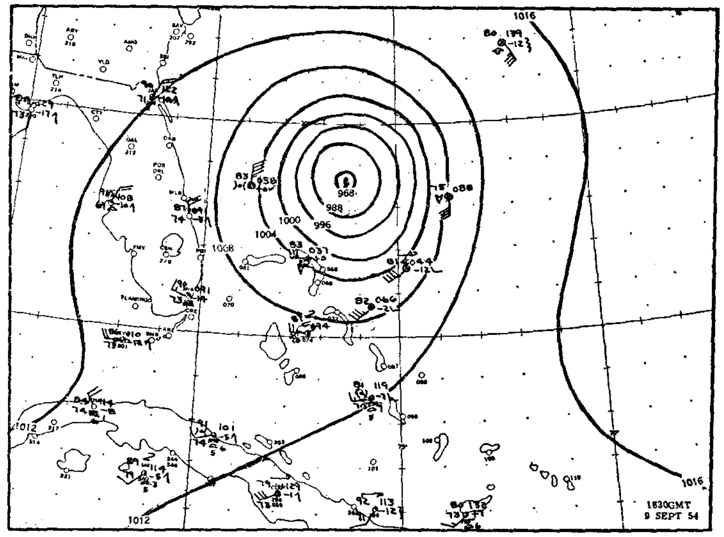


FIGURE 6.—Surface weather chart for 1830 GMT, September 9, 1954. At this time Edna was believed to be in the mature stage. To avoid crowding, several isobars have been omitted.

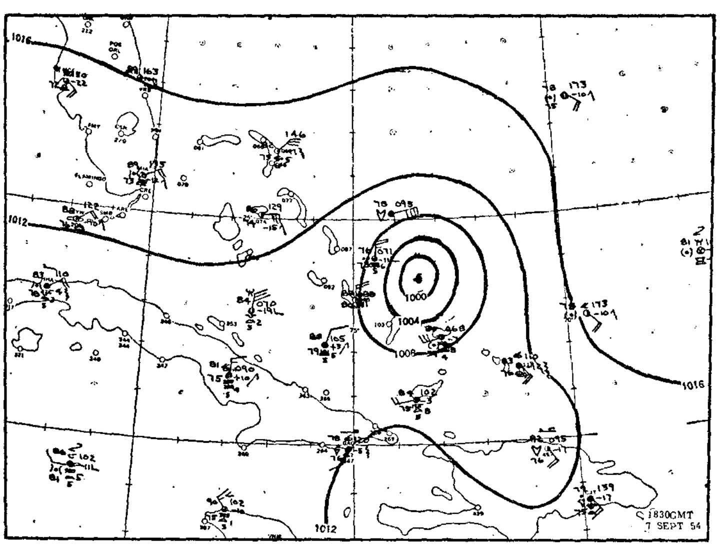


FIGURE 5.—Surface weather chart for 1830 GMT, September 7, 1954. At this time Edna was believed to be in the immature stage.

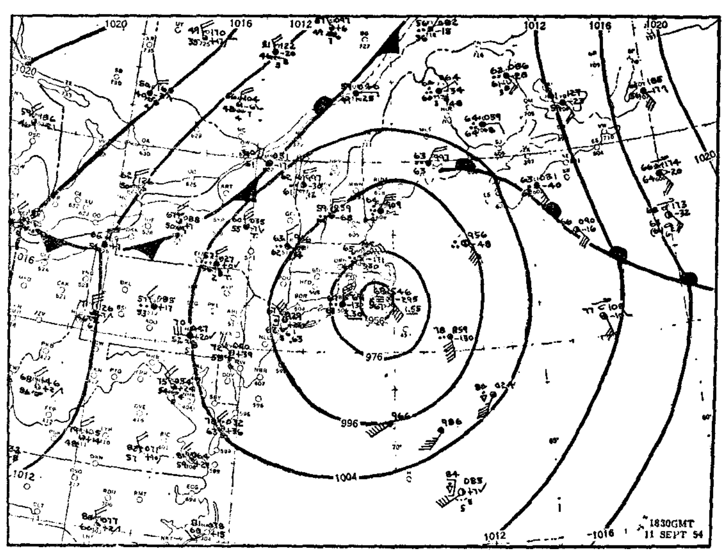


FIGURE 7.—Surface weather chart for 1830 GMT, September 11, 1954.

the general direction of Cape Hatteras. Stations on the southeastern seaboard began to report rapidly increasing cloudiness. A weak quasi-stationary surface front extended eastward along the southern Tennessee border to South Carolina and thence northeastward into the Atlantic, but there was little weather associated with this diffuse front. As the hurricane progressed northward, the onshore winds increased in speed and the cloudiness spread inland from the Carolinas through Pennsylvania. The Appalachian Mountains and the quasi-stationary front with its cooler air to the north, served as a barrier, promoting upslope motion, thereby increasing the cloud cover. Over New England, the flow was also onshore due to the presence of a ridge of high pressure to the northeast, which accounted for the cloudiness that already existed there. By 0630 GMT, September 10, all States on the Atlantic coast north of the Carolinas were covered by a continuous cloud deck.

Meanwhile, an occluded Low, with its associated precipitation pattern, was centered over Lake Michigan and moving eastward. At this time also, rain from the hurricane began to fall along the coast of the Carolinas. At 2130 GMT, September 10, Edna was located just south of Cape Hatteras and the rain area had spread inland and northward to New Jersey. The weak quasi-stationary front extending eastward across the coast and into the Atlantic was torn apart as the hurricane circulation moved northward. By 0630 GMT of the 11th, Edna was about 115 miles northeast of Cape Hatteras and moving toward New England at a comparatively fast speed. The occluded Low moving east from the Great Lakes was then filling. As Edna moved toward New England, stations along and near the coast reported rapid clearing and cessation of rain, soon after the storm center passed to the north of their respective latitudes. Meanwhile, in the New England area, the rains had intensified to a steady downpour and the winds had increased to gale force with frequent strong gusts. At 0030 GMT, September 12, Edna was centered just a few miles west of Eastport, Maine, having passed directly over Cape Cod. Soon thereafter, communications in the area were disrupted, and it was difficult to accurately determine the position of the storm. Continued rapid northeastward movement was subsequently verified.

Definite criteria are not available to fix the time at which Edna became extratropical or entered into the decaying stage. As the storm moved away from New England, it followed the trough along a cold front into a Low to the north (see fig. 7) a sequence of events which is known to forecasters to be conducive to only slow decrease in intensity. Other symptoms of the decaying stage that are considered to be typical include decrease in size after recurvature and upon entering the westerlies, and loss of tropical characteristics while becoming extratropical. After moving up through Canada, Edna, then an extratropical storm, passed into the Atlantic on a track toward the east.

ASPECTS OF THE VERTICAL STRUCTURE

Figure 8 is a space cross section through the eye of Edna, showing constant pressure and thickness profiles. The dropsonde in the eye was released at 700 mb., and the sounding extrapolated up to 125 mb., taking into consideration mean eye values shown by Riehl [2]. This extrapolated portion of the sounding may be somewhat too cold in the region just above 700 mb. Over the eye, the tropopause was considered to lie above 125 mb. At the time of the cross section, Edna was centered just southwest of Nantucket and moving toward an extratropical Low located to the north in Canada. While Edna was still of tropical structure, she was now in the vicinity of an upper cold Low, and subject to modifications from this source as well as from the extratropical air now enveloping the area at the surface.

If thicknesses are chosen for constant pressure surfaces such that these constant pressures are always in the same ratio, then from hydrostatic considerations, equal thicknesses will have the same mean virtual temperature. The constant pressure surfaces in figure 8 were selected with this relationship in mind. The height and thickness profiles illustrate that the low central pressure (946 mb.) was not counterbalanced by the warm core, even to 125 mb., there being some trace of gradient cyclonic flow even at this level. At Cape Hatteras, N. C., the tropopause was at 93 mb., and at Caribou, Maine, it was located at 145 mb. Large differences in temperature of the lower stratosphere were associated with the change in slope of the 62.5-mb surface. For while the 125-mb. level was 440 feet lower at Caribou than at Cape Hatteras, the 62.5-mb. level was 100 feet higher at Caribou. So the layer 125 mb. to 62.5 mb. was 540 feet thicker at Caribou than at Cape Hatteras. Since for thicknesses whose constant pressure surfaces are in the ratio of 2:1, a difference of 200 feet equals a difference in temperature of 3° C., the layer 125 mb. to 62.5 mb. was about 8.1° C. warmer at Caribou than at Cape Hatteras. Data were not available near the eye at these high levels, and a similar thickness comparison there is consequently not given.

Of the several thicknesses, the 500 mb. to 250 mb. stratum showed the greatest thickness variation between the eye and the two stations at the extremities of the cross section. From figure 8, the variation in thickness for this stratum between Cape Hatteras and the eye was 740 feet (about 11.0° C.), while the variation in thickness of the stratum between the eye and Caribou was 900 feet (about 13.4° C.). Some of this 900-foot variation was related to the cold Low situated to the north of Caribou.

It can be seen from figure 8 that the strongest gradients in the constant pressure profiles occurred near the eye of the hurricane, where the strongest winds were observed. The gradient decreased with altitude, and the winds likewise. Thus, the thermal winds around the eye were anticyclonic, and this agrees with the structure of a warm core Low.

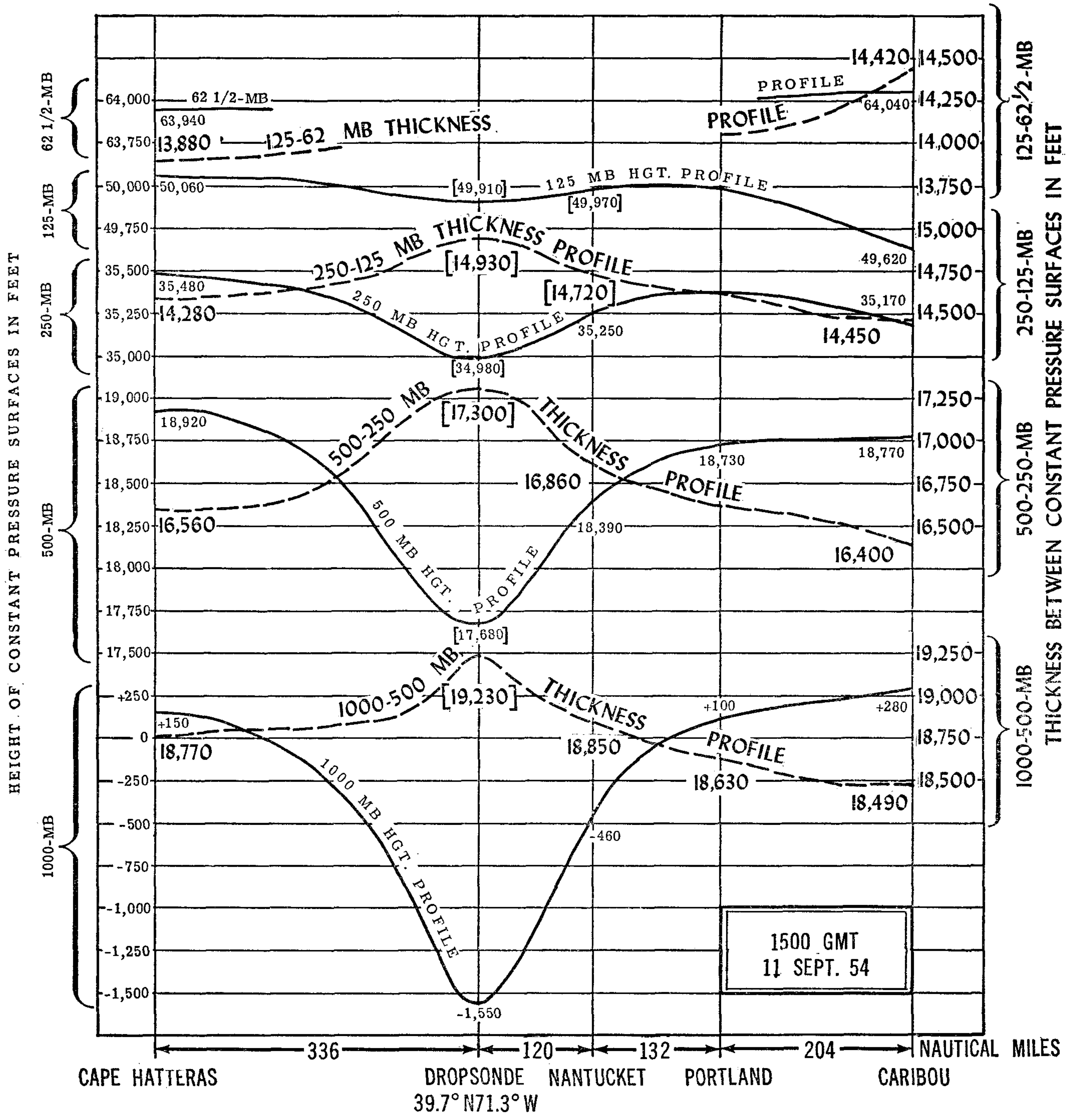


FIGURE 8.—Cross section for 1500 GMT, September 11, 1954, through the eye of Edna. The dropsonde was made in the eye. Heights of constant pressure surfaces are shown as dashed lines. Figures over stations are height and thickness values. Brackets indicate approximations.

SECONDARY DIP IN BAROGRAM

In figure 9, selected barograph traces from hurricanes Carol and Hazel have been superimposed over that of Edna. The secondary dip, not present with Edna, is a distinct and surprising feature in the traces of the other two. These secondary pressure troughs are astonishingly like the dip shown by Pierce [8] on the barograms of the New England hurricane of September 21, 1938. All traces examined indicate the duration of falling pressure to be about 15 minutes.

The explanation of the dip offered by Pierce [8] was the presence of another cyclonic circulation within the main storm. If so, this would be in contrast to the known instances of tornado type vortices embedded within hurricanes, which to this date, have only been observed in the forward semicircle of the advancing tropical storm [9]. Several meteorological conditions associated with

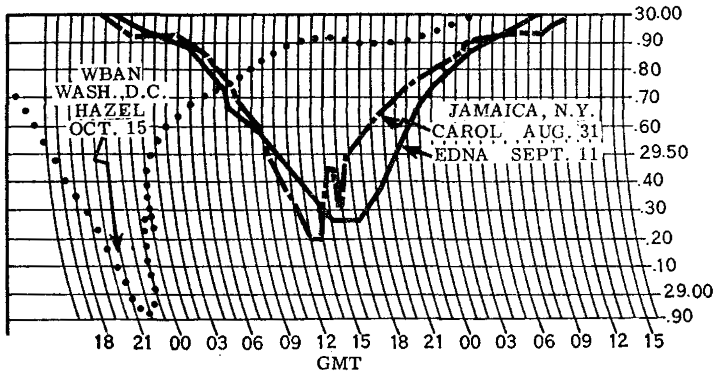


FIGURE 9.—Barograph traces showing secondary falls after passage of main center. Dates after name of hurricane denote date of lowest pressure.

Edna might reasonably have been expected to show the dip that, contrariwise, did not materialize. For example, forecasters were surprised by the strong northwest winds in eastern Massachusetts that were observed several hours after the occurrence of the lowest pressure. Furthermore, the press raised considerable comment about a double eye, and some pilots reported noting visually two cyclonic circulations over the Cape Cod area. A more complete explanation of this secondary fall of the barometer, and its possible relationship to the mechanics of a decaying hurricane, should provide an interesting subject for research.

500-MB. FLOW OVER THE STORM

Figure 10 shows the flow at 500 mb. in the neighborhood of Edna at a time shortly after recurvature, but when the center had surprisingly begun to decelerate. This situation therefore represented a difficult forecasting problem. What actually transpired, in preparing the forecast, involved among other considerations, a decision to place heavy dependence on the Petterssen wave speed equation [10] for the eastward movement of the 500-mb. trough extending through Wisconsin at 0300 GMT, September 10. This computation moved the trough axis to central Pennsylvania on 1500 GMT of the 11th, requiring southwesterly flow aloft along the Atlantic Coast at verification time. The storm was accordingly steered in a direction consistent with these developments aloft, and was forecast to pass over the Cape Cod area [11].

The forecast based on upper air information available 12 hours later, 1500 GMT, September 10 (fig. 11), was slightly less perplexing, in that the trough was advancing at a uniform speed, and the hurricane center, by 1830 GMT of the 11th, was again accelerating northward, thereby increasing the probability of Edna being "picked up" by the trough aloft.

SURFACE STREAMLINE ANALYSIS

Further interest has recently been aroused by Sherman and Carino [12] and Sherman [13] in the advantages of definitely locating singular points when performing streamline analysis in the neighborhood of tropical storms. Such an analysis involves locating not only the positive, cyclonic indraft point, but also a negative, so-called hyperbolic point, where the wind direction is likewise not defined, and consequently the wind speed is zero. An example of such an analysis is shown in figure 12. Several diagrammatic views of flow and streamline analyses involving hurricanes, vividly protraying the hyperbolic point, have been prepared by Wobus [14]. The hyperbolic and cyclonic-indraft points are supposed to be related to the embedding current. One such relationship involves the orientation of the hyperbolic point from the storm center. The point is frequently located in the left forward quadrant of a tropical storm, and if rapid changes in orientation occur, recurvature may be anticipated even while more positive indications are still lacking. It may therefore be appropriate to relate briefly some of the results of such an

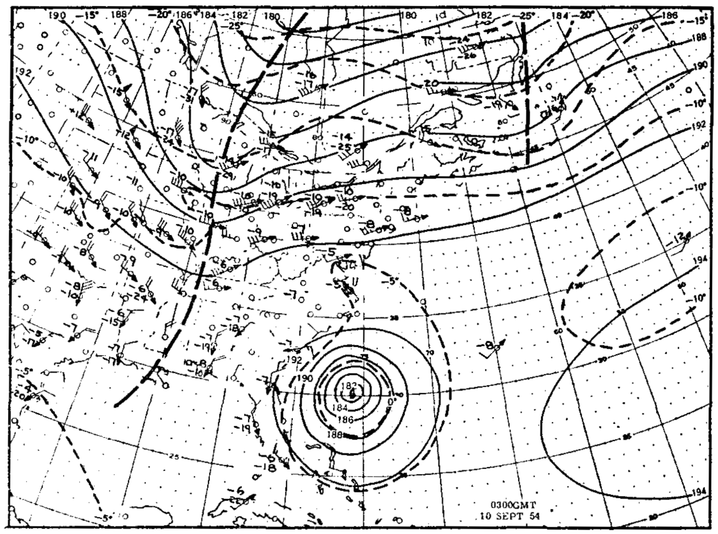


FIGURE 10.—500-mb. chart for 0300 GMT, September 10, 1954. Contours (solid lines) are in hundreds of geopotential feet. Isotherms (dashed lines) are in °C. Troughs are shown as heavy dashed lines. At this time Edna was not in the westerlies.

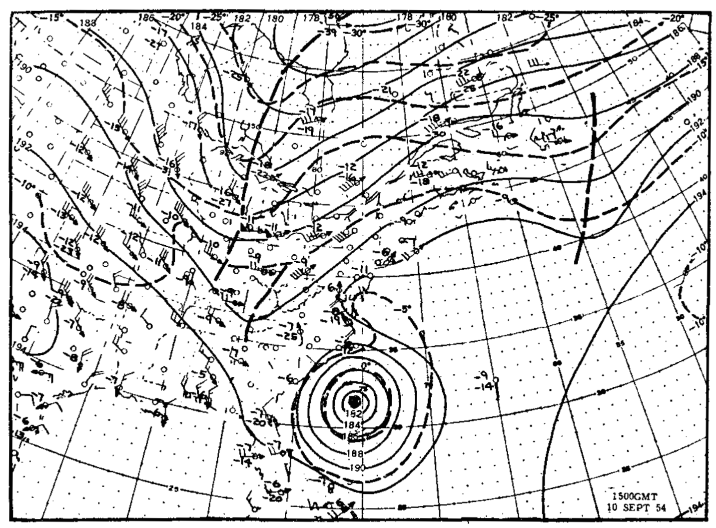


FIGURE 11.—500-mb. chart for 1500 GMT, September 10, 1954.

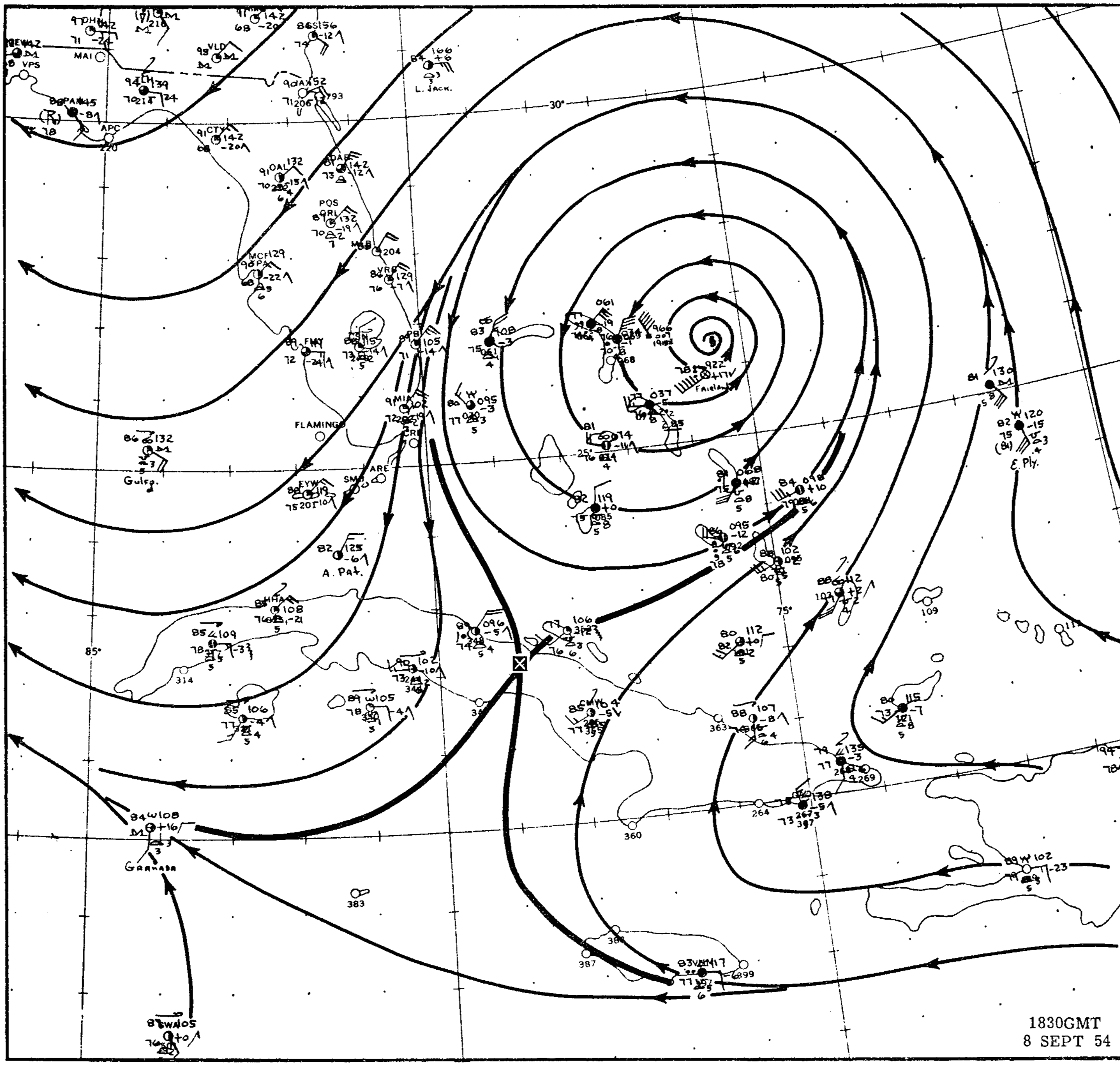


FIGURE 12.—Sample surface streamline analysis (as prepared under operational conditions). Heavy lines illustrate axes of inflow and outflow, and "X" marks the hyperbolic point. Data are from surface weather reports for 1830 GMT, September 8, 1954.

analysis of Edna for the surface level. As our interest was in the value of such an analysis from an operational standpoint under time limitations our streamlines were sketched rapidly, based on only hasty judgments concerning the reliability of questionable wind reports. The period selected for the analysis was from 0030 GMT September 6 to 0030 GMT September 10 inclusive, an interval which covered all the 6-hourly surface maps from the time of formation of Edna until just after recurvature would have been evident from the usual indications.

Following the procedure of Sherman and Carino [12], the analyses were performed by two analysts working independently. In figure 13 we have superimposed the track of the hyperbolic points obtained by one analyst over that obtained by the other, as a means of comparing the extent of agreement between them. This summary of the tracks of the hyperbolic points may be compared with a similar figure given by Sherman and Carino [12]. We have no intent of drawing any general conclusions from just this one case, of the usefulness in current synoptic practice

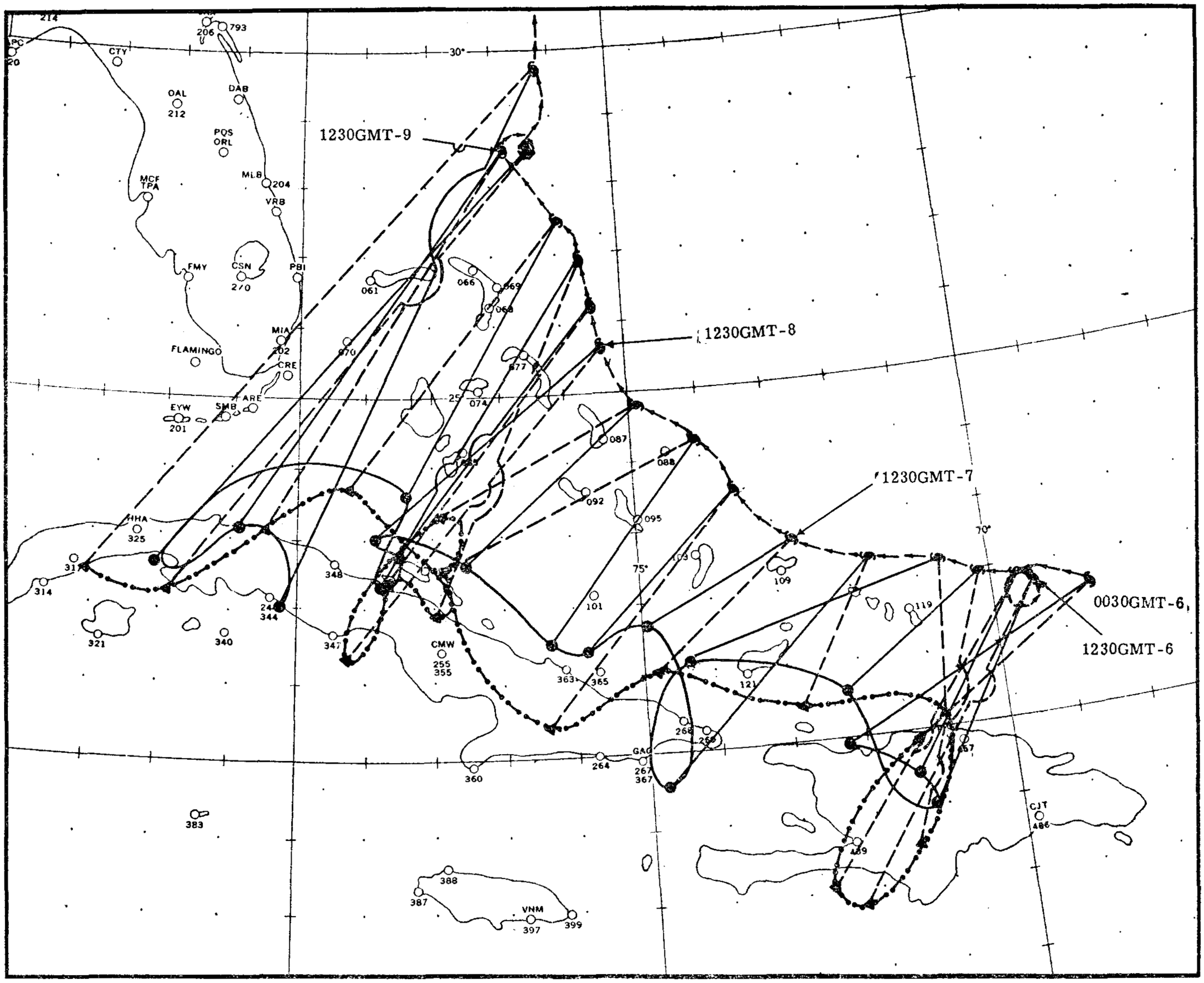


FIGURE 13.—6-hourly positions of hurricane Edna shown by conventional symbol; first analyst's position for the hyperbolic point by solid dots (track of points by solid line), second analyst's by solid triangles (track of points by dashed line).

of analyzing with special attention to the hyperbolic point. We were impressed in several instances by the inability of the analysts to reach reasonably close agreement on the location of the point, due principally, we all felt, to sparsity of data. From an after-casting standpoint, there are indications that at those times when the storm center is moving more erratically and slowly, such as when looping, the hyperbolic point fluctuates correspondingly.

STEERING ASPECTS

In attempting to forecast the movement of hurricanes, meteorologists have for many years given considerable attention and a wide range of interpretation to the rather vague concept of steering. Some interpretations of the steering principle are based on reasoning as stated by James [15] that "if a vortex is embedded in a constant wind field it will move in the direction of the general wind, and the maximum wind around it will have the same direction owing to the mutual reinforcement of the two systems." "This," James continues, "is the kinematic basis of the forecasting rule that a closed pressure system tends to move in the direction of the strongest wind about it." Because it is necessary "to identify a general circulation of dimensions large compared with those of the individual vortices, prognostications of the kinematic theory are valuable only in the case of disturbances of small dimensions such as tropical cyclones." Like many other forecasting precepts, there have been instances when steering has appeared to give erroneous results or has been difficult to apply because of data deficiencies, as for example in the case of typhoon Doris, 1950 in which different steering results were obtained by different analysts (see [16] and [17]).

Without enumerating the variety of views on the subject, the idea of some single level serving to determine *per se* the speed and direction of a hurricane has been demonstrated by Jordan [18] to be an over-simplification of the problem, and she holds that steering involves the determination of a mean wind representative of the greater part of the troposphere. Jordan showed that, on the average, tropical storms were steered by the pressure-weighted mean flow from the surface to 300 mb. and extending 4° of latitude from either side of the storm. The above relation, it must be remembered, has been shown to hold only when observations are averaged for a large number of storms. In individual instances faced by the forecaster, and in our study of Edna, a serious obstacle to computation of such a pressure-weighted flow is lack of sufficient, if any, wind reports within reasonable distances of the tropical storm at necessary times. Thus we were led to make some trial pressure-weighted wind computations using the geostrophic wind, as measured from the contour spacing on the constant pressure level analyses, at all points where wind observations were lacking. In the few instances where the contours had considerable curvature, the gradient wind was used. Usually, where data are sparse, and especially at low altitudes, one is apt to feel lack of confidence in winds estimated from such geostrophic computations. But the use of such estimates seemed to be the best currently available under operational circumstances. The analyses of all levels below 200 mb. had been made consistent by differential techniques, which offered some encouragement. Because our initial misgivings changed to some surprise at the results obtained from several of such computations, they are briefly described in the following.

The computations of pressure-weighted wind values were made at selected positions along the track of Edna corresponding to times when the future movements were most uncertain or otherwise crucial from a forecasting standpoint. The aim was to compare the pressure-weighted wind in the vicinity of the storm with the actual observed instantaneous motion of the hurricane center taken from observed positions along the track. The computations depend for the most part on geostrophic approximations that would have been available to the forecasters.

Four points at 6° of latitude from each storm center location were taken for evaluation; one point to the left and another to the right, and one to the front and another to the rear of the storm. The distance of 6° of latitude was selected because such a radius, with respect to the average size of Edna along this portion of the track, extended to just beyond the area of winds moving in an apparently closed circulation. The hurricane was assumed to be vertical at all times. The winds were determined over each point at 1,000, 850, 700, 500, 300, and 200 mb. Thus, winds from each of the constant pressure analyses regularly prepared in the WBAN Analysis Center were weighted, with the exception of those from the 150-mb. chart. Each wind was broken up into north or south and east or west components. Then, somewhat after the manner used by Jordan [18], components from the points to the left and right of the center were added vectorially, reduced by one-half, and then weighted at each respective level, and then divided by the sum of the weights. The identical process was carried out for each pair of winds to the front and rear of the hurricane, thereby obtaining what may be considered the cross-current correction to the tangential steering component. The tangential and cross-current weighted winds were added vectorially to get the resultant pressure-weighted average wind.

The weights assigned to the winds at the respective upper levels were determined by the pressure differences between top and bottom of the corresponding strata, as indicated in table 1.

TABLE 1.—*Wind levels and corresponding strata and weights used in computing pressure-weighted winds*

Wind level (mb.)	Stratum (mb.)	Weight
1,000	1,000–900	100
850	900–800	100
700	800–600	200
500	600–400	200
300	400–250	150
200	250–200	50

TABLE 2.—*Pressure-weighted winds and corresponding instantaneous velocities of Edna at the times indicated*

Time (GMT)	Date September	Velocity of center		Velocity of pressure-weighted wind	
		Direction (degrees)	Speed (knots)	Direction (degrees)	Speed (knots)
0300	6	115	10	100	08
1500	6	115	7.5	110	07
1500	9	205	5	200	07
0300	11	210	24	220	28

A comparison between instantaneous velocities of Edna, as estimated from the track, and the velocities of the corresponding pressure-weighted winds representative of the environment, is shown in table 2. The degree of agreement with respect to both direction and speed is, we feel, encouraging for further individual applications of the pressure-weighted wind technique. The results also seem to reflect credit on the consistency obtained from the differential techniques used in the preparation of the constant pressure analyses. It was noted that in the first two computations when the storm was moving essentially westward, the actual velocity of the center was slightly to the north of the direction given by the pressure-weighted wind. An interesting speculation is that this might be accounted for by what has been called the Rossby effect, by which cyclonic vortices in the Northern Hemisphere are subjected to a slight poleward acceleration due to the variation of the Coriolis parameter across the width of the storm [19].

A semi-objective technique for the prediction of tropical

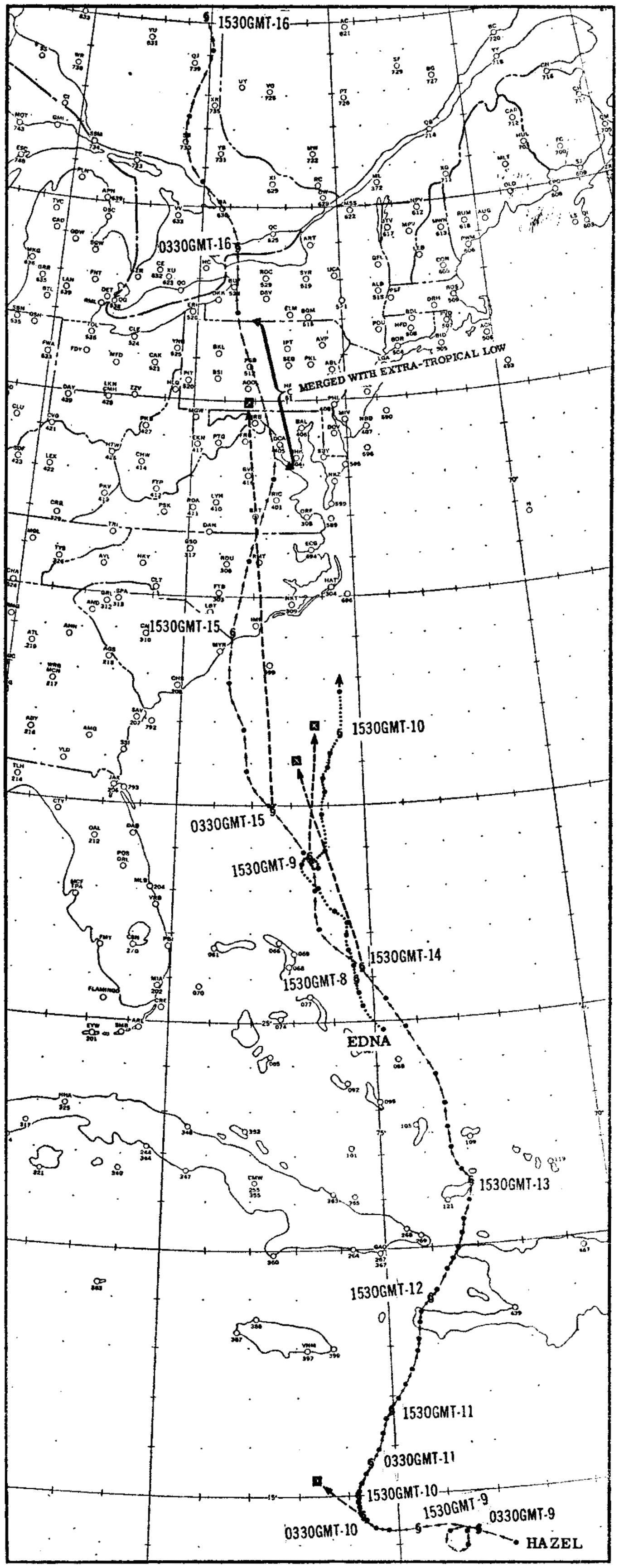


FIGURE 14.—Portions of the observed tracks of Hazel and Edna. The dashed lines ending at the "X's" denote the computed positions 24 hours from the time shown at the beginning of the dashed lines.

cyclone tracks, patterned after the methods used by George and collaborators [20], for forecasting the 24-hour displacement of extratropical storms, has been tentatively established by Riehl and Haggard [21]. While recognizing the influence of the overall tropospheric current, operational exigencies led Riehl and Haggard to search for parameters that would be approximately equivalent to the mean tropospheric flow, yet be based solely on the contour heights at 500 mb.

The Riehl-Haggard computation involves the recording and subsequent manipulation of a set of 500-mb. height values read at points determined by a somewhat variable grid over and surrounding the hurricane center. As the development of the method admittedly emulated the techniques employed by George [20], one is not surprised to find a graph and "types" entering into the calculations. This new technique, incidentally, like the method we used to compute pressure-weighted winds, is indirectly but strongly dependent on geostrophic approximations, and therefore presupposes painstakingly prepared analyses. Furthermore, in making either the pressure-weighted wind or Riehl-Haggard computations, groups of several independent readings or steps are involved, making it difficult to introduce any bias into the final result.

The Riehl-Haggard method was applied once along the track of Edna, when at upper air sounding time the center happened to be located in a critical position with respect to the forecast, and also applied three times along the track of hurricane Hazel, 1954, when the center was similarly located. Because these few trials of this new technique gave useful forecasts in situations selected for their complexity and difficulty, the results have been listed and depicted in table 3 and figure 14, respectively. At those times when the storm center is moving quite slowly, as at 0300 GMT October 10 in the case of Hazel, it is reasonable to expect the forecast system to give much better results for speed than for direction. As can be seen from figure 14, this was the case. Furthermore, the computation made at 0300 GMT on the 15th for Hazel which gave a result that was too slow, may not have been a fair trial of the method, which was not intended to predict movement "after the first day following final recurvature." Judging from these few applications further use of the technique is warranted.

TABLE 3.—*Results of Riehl-Haggard computations at several selected positions along tracks of hurricanes Edna and Hazel, 1954*

Hurricane	Date 1954	Time GMT	Location of center of storm at prog. time	24-hr. displacement of storm in degrees of latitude N–S, in degrees of longitude E–W	
				Actual	Predicted
Edna	9 Sept.	1500	28.6N, 76.5W	3° to N 1° to E	3.2° to N 0.2° to E
Hazel	10 Oct.	0300	14.6N, 75.5W	1° to N 0.2° to E	0.6° to N 0.9° to W
Hazel	14 Oct.	1500	26.4N, 75.4W	7.7° to N 3.4° to W	4.9° to N 1.6° to W
Hazel	15 Oct.	0300	30.0N, 77.7W	14° to N 1.2° to W	10.1° to N 0.6° to W

Charts of mean temperature (thickness) for the 700 to 500-mb. stratum at times shortly after recurvature, 0300 and 1500 GMT, September 10, have been prepared by Simpson [4], and the track that Edna followed does provide an additional case in support of Simpson's theory [22] of warm tongue leading and steering of tropical cyclones.

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